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**APPLICATION FOR UNITED STATES
LETTERS PATENT**

by

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for

**METHOD TO HARDEN SHALLOW TRENCH ISOLATION
AGAINST TOTAL IONIZING DOSE RADIATION**

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Attorney Docket No. 032908-008

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09629172-073100

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**METHOD TO HARDEN SHALLOW TRENCH ISOLATION
AGAINST TOTAL IONIZING DOSE RADIATION**

This disclosure is based upon, and claims priority from, provisional U.S. Patent Application No. 60/146,895, filed August 2, 1999, the contents of which are incorporated herein by reference.

BACKGROUND OF THE INVENTION

1. Technical Field

The present invention relates to integrated circuits in general, and in particular to a method for fabricating integrated circuit devices. Still more particularly, the present invention relates to an enhanced shallow trench isolation method for fabricating radiation-tolerant integrated circuit devices.

2. Description of the Prior Art

Within a semiconductor integrated circuit (IC) device, device isolation regions can typically be found between two adjacent active components to prevent carriers from traveling between the two adjacent active components. For example, device isolation regions are conventionally formed between two adjacent field effect transistors (FETs) to reduce charge leakage to and from the two FETs. Often, device isolation regions take the form of thick field oxide regions extending below the surface of a semiconductor substrate. The most common technique for forming a thick field oxide region is to use a local oxidation of silicon (LOCOS) processing technique that is well-known to those skilled in the art of semiconductor processing. Details related to the LOCOS processing techniques can be found in *VLSI technology*, S. M. Sze, McGraw-Hill, 1983, which is incorporated by reference herein.

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1 However, bird's beak regions formed in the LOCOS growth of
2 field oxide regions are undesirable because they are typically too thin to
3 provide any impact in terms of device isolation. Bird's beak regions
4 nevertheless consume substrate surface area, limiting the extent to which the
5 field oxide region can be shrunk while still providing desirable levels of device
6 isolation. To provide higher device densities, it is therefore desirable to utilize
7 a better device isolation structure such as shallow trench isolation (STI). With
8 STI technology, a sharply defined trench is formed in the semiconductor
9 substrate by, for example, anisotropic etching. The trench is filled with oxide
10 back to the surface of a semiconductor substrate to provide a device isolation
11 region. Trench isolation regions formed by STI have the advantages of
12 providing device isolation across their entire lateral extent and of providing a
13 more planar structure.

14
15 The present disclosure provides an improved STI method for
16 fabricating a shallow trench that yields a desirable level of radiation tolerance
17 so that the resulting semiconductor IC device can be used in high-radiation
18 environments. Radiation tolerance refers to the ability of a semiconductor IC
19 device to withstand radiation without alteration of its electrical characteristics.
20 A semiconductor IC device is said to be radiation tolerant if it can continue to
21 function within specifications after exposure to a specified amount of
22 radiation.

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SUMMARY OF THE INVENTION

1
2
3 In accordance with a preferred embodiment of the present
4 invention, a layer of pad oxide is first deposited on a semiconductor substrate.
5 A layer of pad nitride is then deposited on the pad oxide layer. A trench is
6 defined within the semiconductor substrate by selectively etching the pad
7 nitride layer, the pad oxide layer, and the semiconductor substrate. Boron ions
8 are then implanted into both the bottom and along the sidewalls of the trench.
9 Subsequently, a trench plug is formed within the trench by depositing an
10 insulating material into the trench and by removing an excess portion of the
11 insulating material. Since the boron ions are implanted at an angle during the
12 above-mentioned ion implantation step, the semiconductor IC device
13 advantageously exhibits enhanced radiation-tolerance.

14 As further steps, a p-well is implanted to a depth just below the depth
15 of the bottom of the trench. This helps to keep the threshold voltage of the
16 IC device below the trench at a high level, and thereby keep post-radiation
17 leakage low. Then, an electrically neutral species is implanted into the wafer.
18 This implant can be a blanket implant over the whole wafer, or p-channel
19 devices can be shielded from the implant.

20 Each of these steps can be individually employed to increase radiation
21 hardness over conventional levels. However, the best results are achieved
22 when all of the steps are employed in conjunction with one another.
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BRIEF DESCRIPTION OF THE DRAWINGS

The invention itself, as well as a preferred mode of use, further objects, and advantages thereof, will best be understood by reference to the following detailed description of an illustrative embodiment when read in conjunction with the accompanying drawings, wherein:

Figure 1 is a pictorial diagram of a semiconductor substrate having a layer of pad oxide and a layer of pad nitride, in accordance with a preferred embodiment of the present invention;

Figure 2 illustrates the formation of a trench definition mask on the semiconductor substrate from Figure 1, in accordance with a preferred embodiment of the present invention;

Figure 3 illustrates the formation of a trench on the semiconductor substrate from Figure 1, in accordance with a preferred embodiment of the present invention;

Figure 4 is a pictorial illustration of the directional boron implantations, in accordance with a first aspect of the present invention;

Figures 5-8 illustrate the formation of a trench plug on the semiconductor substrate from Figure 1, in accordance with a preferred embodiment of the present invention;

Figure 9 illustrates the formation of a P-well, in accordance with a second aspect of the invention; and

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Figure 10 illustrates the implantation of an electrically neutral material, in accordance with a third aspect of the invention.

DETAILED DESCRIPTION OF A PREFERRED EMBODIMENT

The present invention provides an enhanced shallow trench isolation (STI) method for fabricating radiation tolerant semiconductor integrated circuit (IC) devices, and a preferred embodiment will be described in detail with reference to the accompanying drawings. The fabrication process begins with the division of a semiconductor substrate into active regions where active electrical components are to be formed, and isolation regions that electrically separate the active regions.

Referring now to the drawings and in particular to Figure 1, there is illustrated a pictorial diagram of a semiconductor substrate having a layer of pad oxide and a layer of pad nitride, in accordance with a preferred embodiment of the present invention. As shown, a silicon substrate 10 is coated with a layer of thermal oxide that acts as a pad oxide layer 11. Pad oxide layer 11 protects the surface of substrate 10 from damage in subsequent processing steps. For this purpose, the pad oxide layer has a thickness of approximately 100Å - 300Å. In addition, a layer of silicon nitride that serves as a pad nitride layer 12 is formed on top of pad oxide layer 11. Pad nitride layer 12 may be deposited by chemical vapor deposition (CVD) to a thickness of 1000-3000 Å.

Next, a trench definition mask 14, as depicted in Figure 2, is formed by exposing and etching a layer of photoresist that was deposited onto pad nitride layer 12. Trench definition mask 14 is shaped in the usual manner

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so that the surface of pad nitride layer 12 is exposed at a region x where a trench will be formed. Trench definition mask 14 may itself be used as the mask for etching layers 12 and 11 as well as substrate 10 in forming a trench, or trench definition mask 14 may be used to define a mask in pad nitride layer 12 that can then be used for subsequent etching steps. Most often, a photoresist mask is used to define the lateral extent of all of the etching steps used in the formation of a trench in substrate 10 because fewer processing steps are involved.

A trench 15 is then formed in substrate 10, as illustrated in Figure 3, by consecutively etching pad nitride layer 12, pad oxide layer 11, and substrate 10. The etching processes used are preferably anisotropic and may, for example, be performed by reactive ion etching (RIE). For example, a gas etchant, such as CF_4 and O_2 , is used to etch pad nitride layer 12 and pad oxide layer 11. Substrate 10 is etched using RIE and a mixture of gases including Cl_2 , O_2 , HBr , and He . The bottom portion of trench 15 can be etched using SF_6 so that the transition between the bottom and sidewalls of trench 15 is rounded. An appropriate trench depth for forming a shallow trench isolation is approximately 2000Å-5000Å deep. Trench definition mask 14 can be removed at this point. If desired, a thin thermal oxide layer (*i.e.*, sidewall oxide) may be grown on the sidewalls and bottom of trench 15 to remove any defects created by the etching processes. If such a thin thermal oxide layer is formed, the thin thermal oxide layer may either be left in place to become part of a trench plug (such as trench plug 17 shown in Figure 6) or be removed.

With reference now to Figure 4, there is illustrated a pictorial illustration of directional boron ion implantations, in accordance with one

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1 aspect of the present invention. As indicated by arrows **31**, boron ions are
2 first introduced at an angle in a range of about 0° - 7° from a vertical axis.
3 Subsequently, a second implantation **32** at a higher angle, in the range of 30° -
4 45° , is carried out. The boron ion implantation steps preferably have the
5 following parameters: an energy in a relatively low range of about 20 KeV or
6 less, and a concentration of boron ions in a range between approximately 10^{10}
7 atoms/cm² and 10^{13} atoms/cm². If there is a sidewall oxide deposited within
8 trench **15**, the energy of the boron ion implantation should be high enough for
9 the boron ions to penetrate through the sidewall oxide and stop in substrate
10 **10**. Also shown in Figure 4 is the area of boron ion implantation within
11 substrate **10**, which is marked by a dotted line **33**.

12
13 The low-angle implant provides a high pre-radiation threshold
14 voltage beneath the trench. Hence, even if a substantial amount of positive
15 charge is trapped in the trench during irradiation, the field threshold remains
16 high, and no radiation-induced leakage occurs between neighboring n-channel
17 transistors. The higher-angle implant provides similar results to create a high
18 threshold voltage along the side walls of the trench. This helps to keep
19 radiation-induced leakage low along the parasitic sidewall path that typically
20 occurs between the source and drain within an n-channel transistor.

21
22 The implantation of the boron ions at an angle into the field
23 isolation area can be carried out in a number of different ways. For example,
24 an ion beam generator can be mounted in a manner such that it can be pivoted
25 relative to the semiconductor substrate, to emit a beam of ions at any desired
26 angle relative to the substrate. More preferably, however, the substrate is
27 mounted on a pivoted or gimbaled platform, so that its orientation relative to
28 a fixed ion beam generator can be varied during the implantation process, to

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1 receive the beam of ions at the desired angle. Further, although two separate
2 implantation steps have been described for the bottom and side walls of the
3 trench, a single continuous implantation could be carried out as well. If
4 desired, conventional lithography techniques can be used to protect p-channel
5 areas from the boron implant.

6
7 Next, trench 15 is filled with a layer of silicon oxide 16 by, for
8 example, low pressure chemical vapor deposition (LPCVD) using
9 tetraethylortho-siloxane (TEOS) as a source gas. Trench 15 is overfilled during
10 deposition, as shown in Figure 5, in order to achieve good planarization during
11 subsequent CMP process and to account for possible densification.
12 Densification of the TEOS oxide is preferably accomplished at a temperature
13 of approximately 1000°C for 10-30 minutes. After densification, the portion
14 of the TEOS oxide layer extending above pad nitride layer 12 is removed by
15 chemical mechanical polishing (CMP) using pad nitride layer 12 as a stop for
16 the polishing process. After the CMP process, some oxide is left inside trench
17 15 to form a trench plug 17, as depicted in Figure 6. Although not clearly
18 shown in Figure 6, the surface of trench plug 17 is recessed slightly below the
19 surface of pad nitride layer 12 after the CMP process because the silicon oxide
20 in trench plug 17 is softer than the silicon nitride in pad nitride layer 12.

21
22 Pad nitride layer 12 is subsequently removed to expose pad oxide
23 layer 11, typically leaving a portion of trench plug 17 extending above the
24 surface of pad oxide layer 11, as illustrated in Figure 7. A hydrofluoric acid
25 dip is then used to remove pad oxide layer 11, resulting a structure shown in
26 Figure 8. A greater depth of trench plug 17 than that of pad oxide layer 11
27 is removed during this etching process because trench plug 17, which is

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1 formed of TEOS, is etched more rapidly than pad oxide layer 11, which is
2 formed of thermal oxide.

3
4 A sacrificial oxide layer 18 is grown on the surface of substrate
5 10 for protecting the surface of substrate 10 and for limiting the channeling
6 of ions implanted in subsequent ion implantation steps. A p-type dopant, such
7 as boron or indium, is then implanted to form a P-well 19, as depicted in
8 Figure 9. As a second feature of the invention, the energy of the implant is
9 determined so that the depth of the well 19 is just below the bottom of the
10 trench 15. This arrangement helps to keep the threshold beneath the trench
11 at a high level, so that post-radiation leakage remains low.

12
13 In an embodiment of the invention where the P-well is formed by
14 a boron implant, the step of implanting the boron can be carried out in
15 conjunction with, or as part of, the low-angle boron implant 31 that occurs
16 prior to filling the trench. Also, conventional photolithography processes can
17 be used to cover p-channel devices during this implant.

18
19 As a third step in the radiation hardening of the IC device, an
20 electrically neutral species, such as germanium, is implanted into the wafer.
21 In carrying out this step, a blanket implant can be performed over the entire
22 wafer, as shown in Figure 10, or photolithography techniques can be
23 employed to shield p-channel devices from the implanted ions. Preferably,
24 high dosage levels are used for this implant, for example around 10^{13}
25 atoms/cm² or higher. The implant energy is adjusted to correspond to the
26 implant depth of the n-channel transistors 34, or both n- and p-channels if a
27 blanket implant is utilized. More specifically, the energy of the implant should
28 be regulated to limit the implantation to a depth 35 which ensures that the

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1 electrically neutral species remain in the n^+ and p^+ diffusion regions. If the
2 implant extends into the junction between these diffusion regions and the
3 well, the diode which results from this junction could be leaky.

4
5 Sacrificial oxide layer 18 is subsequently removed, once again
6 using a hydrofluoric acid dip. The semiconductor substrate is thereafter
7 subjected to further processing to complete a fabrication of a semiconductor
8 IC device. A description of those further processing steps, which are known
9 to those skilled in the relevant art, is not necessary to an understanding of the
10 present invention, and therefore not presented herein.

11
12 As has been described, the present invention provides an
13 enhanced STI method for fabricating radiation-tolerant IC devices. The
14 increase in radiation tolerance is attributable to the implantation of boron ions
15 at an angle during an boron ion implantation step. As a result, a higher p-type
16 concentration can be maintained under the field oxide regions of the substrate.
17 Because of the high p-type concentration in the substrate, the substrate is
18 able to withstand a relatively high dose of radiation before any inversion
19 occurs at the surface of the substrate. Further enhancements are provided by
20 implanting the p-well to a depth just below the bottom of the trench, and by
21 implanting an electrically neutral species into the wafer. In view of such, IC
22 devices that are fabricated using the present invention exhibit enhanced
23 radiation-tolerance.

24
25 While the invention has been particularly shown and described
26 with reference to a preferred embodiment, it will be understood by those
27 skilled in the art that various changes in form and detail may be made therein
without departing from the spirit and scope of the invention.

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